Fragaria xananassa:

Past, Present and Future Production of the Modern Strawberry

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EXECUTIVE SUMMARY

This review considers the history and production of the modern strawberry (*Fragaria* x*ananassa*) in the United States and worldwide. Strawberry production in the Upper Midwest, specifically Minnesota, is limited to traditional outdoor production methods during the growing season. Herein the possibilities for developing indoor, year-round strawberry production in Minnesota are explored. This new market could open the door for growers to sell locally grown strawberries to consumers who have shown a strong affinity for locally grown fruits.

I. INTRODUCTION

A. Study Species.

The modern strawberry, also known as the desert strawberry, or *Fragaria* x*ananassa* Duchense, is a delicious and fascinating fruit. People all around the world have eaten different types of strawberries for thousands of years. Virgil warned children to watch for snakes when they picked the fruit, Native Americans made an early version of strawberry shortcake with ground cornmeal, Anne Boleyn's strawberry shaped birthmark proved to some that she was a witch, and now the United States spends US $5.6 billion a year to grow and eat strawberries (Wolford and Banks 2015, Lawrence 2015). This ubiquitous fruit is the focus of worldwide university research programs, private breeding and growing companies, and backyard and small-scale farmers alike due to its delicious taste, its unusual and interesting evolutionary journey, and because of the many different ways it might be possible to grow the strawberry.

Minnesota currently produces far fewer strawberries than other regions of the United States, namely California or Florida, but residents of the state consume strawberries provided by these regions year-round. The short Minnesota growing season and low USDA hardiness zone do not make Minnesota an ideal place for strawberry production, but the demand for local and sustainable foods suggests a potential market for indoor, containerized strawberry production. This report will discuss the history, distribution, and current production methods and statistics of *F.* x*ananassa* in order to explore the possibilities for future indoor, local Minnesota strawberry production.

B. Taxonomic Classification and Geographic Distribution in the Wild.

The strawberry (*Fragaria spp.)* is in the Rosaceae, along with apples, plums, and several other major fruits. It is a perennial, herbaceous, and diminutive plant, growing low to the ground from a central crown. Roots reach about 15-30 cm into the ground below the crown and live for several years. Most cultivars have trifoliate, compound leaves arranged in a spiral around the crown (Martin and Tepe 2014, Davis 2015). Strawberries reproduce sexually via seed; they can also reproduce asexually using their stolons, or runners, which grow several cm away from the 'mother' plant before rooting into the ground at the nodes and developing a new crown. Several weeks later, the stolon deteriorates and the new 'daughter' clone is independent from its 'mother', eventually growing its own flowers, leaves, and stolon (Martin and Tepe 2014, Davis 2015).

The strawberry 'fruit' is not actually a berry but instead a receptacle for potentially hundreds of tiny fruits, known as achenes. Flowers have five or more white obovate petals that surround up to thirty stamens, which in turn surround a raised, conical receptacle covered in up to 500 pistils, each atop an individual carpel (Galetta and Himelrick 1989). After pollination occurs, this receptacle enlarges and turns red, developing into the 'berry' that we eat. The actual fruits are achenes that develop from each carpel, holding one seed each on the receptacle's surface (Himelrick et al. 2002, Martin and Tepe 2014).

Wild strawberries or native species in the genus *Fragaria* can be found on four different continents (Table 1). Lake Baikal, in Siberia, separates the nearly one dozen Asian cultivars from the two native European species, with at least two cultivars in North America and one in Chile (Davis 2015). The modern, commercially available strawberry is a hybrid of an American and a Chilean wild strawberry, *Fragaria virginiana* and *F. chiloensis*, respectively, and is fully described as *Fragaria* ×*ananassa* Duchesne ex Rozier nothosubsp. *Ananassa* (Hummer and Hancock 2009).

Table 1: Worldwide distribution of native strawberries (*Fragaria* spp.) (Adapted from Hummer and Hancock 2009; GRIN 2015).

Species	Geographic Distribution
F. bucarica Losink.	Asia (W. Himalayas)
F. daltonia J. Gay	Asia (Himalayas)
F. nubicola Lindl.	Asia (Himalayas)
F. gracilis Losink.	Asia (N. China)
F. mandshurica Staudt	Asia (N. China)
F. pentaphylla Losink.	Asia (N. China)
F. corymbosa Losink.	Asia (N. China)
F. moupinensis (French.) Card	Asia (N. China)
F. gracilis Losink.	Asia (N.W. China)
F. tibeticia spec. nov. Staudt	Asia (China)
F. innumae Makino	Asia (Japan)
F. yezoensis Hara.	Asia (Japan)
F. nipponica Lindl.	Asia (Japan)
F. iturupensis Staudt.	Asia (Iturup Island)
F. nilgerrensis Schlect.	Asia (S.E. Asia)
F. orientalis Losink. syn. = *F. corymbosa* Losink.	Asia (China, Far Eastern Russia)
F. Americana (Porter) Britton syn. = *F. vesca* (Porter) Staudt.	Europe, Asia, N. America
F. viridis Duch.	Europe, Asia
F. moschata Duch.	Europe, Asia
F. chilonensis (L.) Miller	N. America, S. America (Western N. America, Hawaii, Chile)
F. virginiana Miller	N. America

Different cultivars of *F. ×ananassa* have been developed for growth in many different climates—anywhere from the taiga to the subtropics. Most commercial production occurs in temperate and Mediterranean climates, between the 42nd north and south parallels. The temperatures in this area ranges from summer highs of 40° C and winter lows of -40° C (Hancock 1999, Lopez-Aranda et al. 2011).

There are two main groups of commercial strawberries grown today, each with many cultivars. 'June-bearing,' or 'short-day' strawberries develop their flower buds in the shorter days of late summer and early fall, overwintering until the following spring when they produce fruit around June in the Northern Hemisphere, or December in the Southern hemisphere. The rest of the summer is dedicated to "runnering" and vegetative growth (Himelrick et al. 2002). June-bearers can also develop flower buds in longer days if the temperature drops below 15° C. 'Day-neutral' berries do not have a photoperiodic requirement for flower bud initiation or development and can fruit throughout the growing season, with the first flower buds appearing around three months after planting. High heat can inhibit bud development in day-neutrals, with an ideal growing temperature thought to be between about 18 and 26° C. Day-neutrals grow vegetatively throughout the growing season. While different cultivars are adapted to different parts of the world, many commercial strawberry cultivars require a dormancy period (Hancock 1999). Section III will discuss modern strawberry production in greater depth.

II. CROP HISTORY

A. Breeding & Domestication.

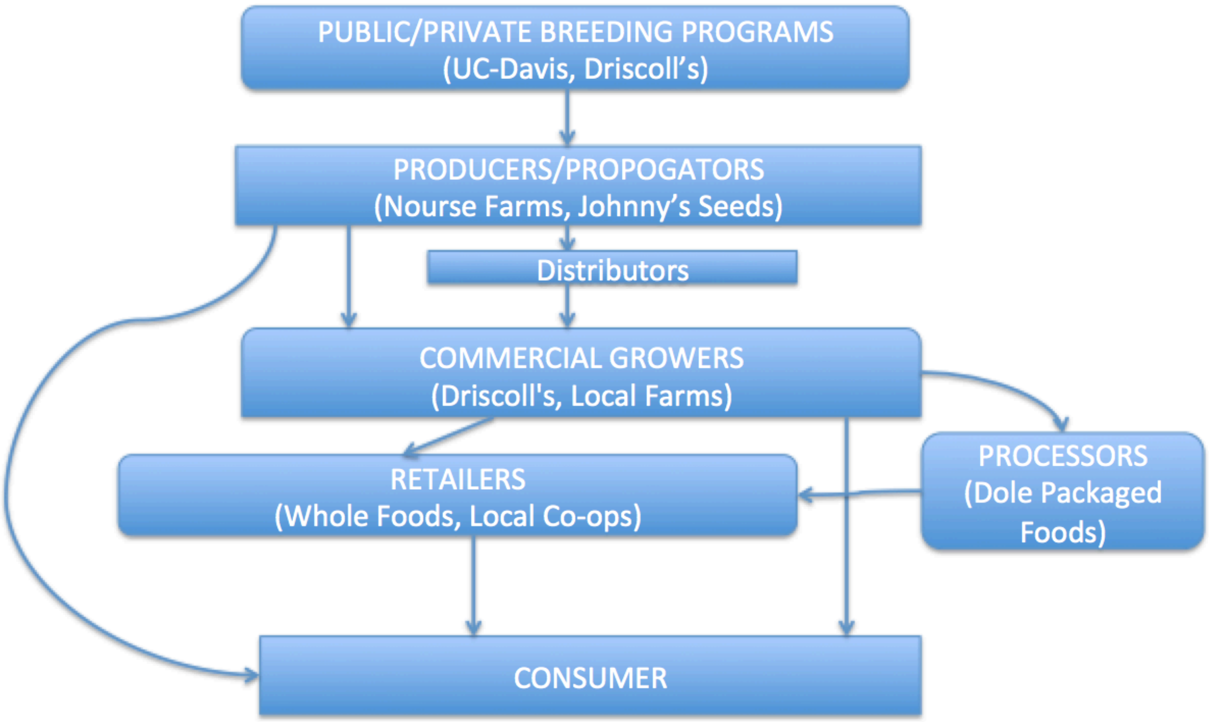
Strawberries have been grown and foraged for millennia, although the modern *F.* ×*ananassa* was not developed until the 18th century (Galetta and Himelrick 1989). Native peoples of North America gathered *F. virginiana*, or Virginia strawberries, with the berries making appearances in Cherokee myths. The Ancient Romans and Greeks grew *F. vesca*, the alpine strawberry native to Europe and North America, for medicinal and landscape purposes initially, later for consumption (Hummer and Hancock 2009). In medieval times, Europeans also cultivated native *F. moschata*, a muskier flavored berry and the green *F. viridis* for ornamental purposes. *Fragaria vesca* dominated cultivation in Europe until the 17th century (with a brief dip in popularity after the 12th century declaration from the abbess Saint Hildegard von Binger that strawberries were not to be eaten, as they grew on the ground among snakes and toads) when *F. virginiana*, recently imported from North America, began to replace it (Hummer and Hancock 2009). In 1716, French spy Amédée Frézier brought the South American *F. chilonensis*, long cultivated by the Mapuche people of Chile, to France. In the 1760s, Nicholas Duchesne, a French botanist, began noticing 'unusual' strawberry seedlings with larger, redder fruit and a sweet smell in gardens in Brittany. By 1766, Duchesne determined that this new cultivar was a cross between *F. virginiana* and *F. chilonensis*. He named the new interspecific hybrid *F. ×ananassa* after the sweet pineapple (*anana* in French) aroma; they spread throughout France and eventually the world (Galletta and Himelrick 1989). *Fragaria vesca* is still grown as a delicacy in some home gardens, while *F. chilonensis* can still be found in parts of Chile, and *F. moschata* and *F. viridis* have declined significantly. All have been replaced by the sweeter, more popular *F. ×ananassa* cultivars (Hummer and Hancock 2009).

Botanists in France and England continued to intercross and select for sweet, well-shaped and well-adapted strawberries, propagating popular cultivars asexually through stolons and/or stolonate crowns (Galetta and Himelrick 1989). Independent botanists and breeders such as Michael Keen and Thomas Knight produced some of the early, most popular cultivars, such as 'Downton' and 'Keen's Seedling,' that served as the forbearers of many modern types. Charles Hovey, a nurseryman, in Massachusetts created the first "American" strawberry, crossing a European cultivar with the native *F. virginiana* to produce the 'Hovey' strawberry in 1836, dominating the American market. Breeding programs also emerged in Japan, where Dr. H. Fukuba developed the 'Fukuba,' noted for its large size (Hancock 1999).

Most strawberry breeding programs have utilized 'elite' parents for intercrossing, though backcrossing, selfing, and occasional inbreeding of different generations has also been used. Native strawberries around the world evolved with different ploidy levels, or different numbers of chromosomes—*Fragaria bucarica* and other Asian strawberries, for example, have two sets of chromosomes, like humans, but *F. iturupensis* has ten. These different chromosome levels can make crossing different species complicated, but exciting for breeders and researchers alike. (Hummer and Hancock 2009). The evolution of strawberry ploidy is not completely understood, but it gives breeders an opportunity to experiment with integrating 'wild' germplasm into the commercial cultivars (Hancock 1999). Day-neutrality, for example, came from a wild selection in the Wasatch Mountains, on the Utah-Idaho State's border (Hancock 2006). Modern breeding programs select for pest resistance, drought, heat, and cold tolerance, flowering habit and fruit quality, yield, and adaptability to mechanical harvest. The presence of stolons makes asexual reproduction of new cultivars particularly easy (Hancock 2009). Propagation via seed is quite rare in the United States, as the varying ploidies of different species can complicate sexual reproduction; asexual propagation is cheaper and straightforward. Japanese researchers have looked into seed propagation as possible method of eliminating viruses or other pathogens (Mauro et al. 2007).

Strawberry breeding programs can be found all across the world, but most are centered in the United States and Europe. The University of California and the University of Florida are two large public sector breeding programs in the United States (Faedi et al. 2002, Whitaker et al. 2011); another is the USDA Horticultural Crops Research Lab in Oregon, which developed the popular 'Hood' cultivar (Hancock 1999, Faedi 2002) as well as the University of Minnesota which developed 'Mesabi' and 'Winona' (Hoover et al., 2015). There are several public breeding programs in Europe as well, such as Wageningen University in The Netherlands, which produced the still popular 'Elsanta'. Private breeding programs expanded worldwide in the 1980s and 1990s, with California's Driscoll Strawberry Associates, a private sector breeder and grower company, dominating in the United States. Other large European private breeders include Centro Innovazione Varietale in Italy and Planasa in Spain (Faedi et al. 2002).

Figure 1: The strawberry distribution chain illustrating examples at each level (Adapted from Hokanson and Finn 2000; Boriss 2006; ERS 2012).



The strawberry distribution chain (Figure 1) consists of public and private breeding programs, such as those mentioned above, which develop cultivars used by producers and propagators. Nourse Farms, for example, grows bare-root strawberry plants to ship to strawberry farms, which grow the plants out and sell the berries to grocery stores, processors who make frozen fruit or other strawberry products or to consumers directly. Consumers can also buy bare-root plants and grow their own berries (Hokanson 2000, Borris 2006). Driscoll's is the major player in many links of the distribution chain—the company breeds its own cultivars, produces the starts, grows the berries, and sells to many retailers. A recent article estimated that Driscoll's held a 34% market share of conventional strawberries in the United Sates and almost 50% in the organic market (Lawrence 2015).

The strawberry breeding world is not without drama—in 2014, The University of California's head strawberry breeder, Doug Shaw, announced that he and his research partner were leaving the University to form a private breeding company. Their announcement set off a series of lawsuits from the California Strawberry Commission, a semi-governmental growers group, who feared that Shaw and his associates would take the University's germplasm repository with them, gutting the University's breeding program and forcing growers to buy more expensive cultivars from private companies. The lawsuit was only recently settled; the University hired a new strawberry breeder and committed to continuing its breeding program for at least five years (Gordon 2015). This incident highlights the importance of public breeding programs for growers like the members of the California Strawberry Commission.

III. PRODUCTION INFORMATION

A. Current Production Practices.

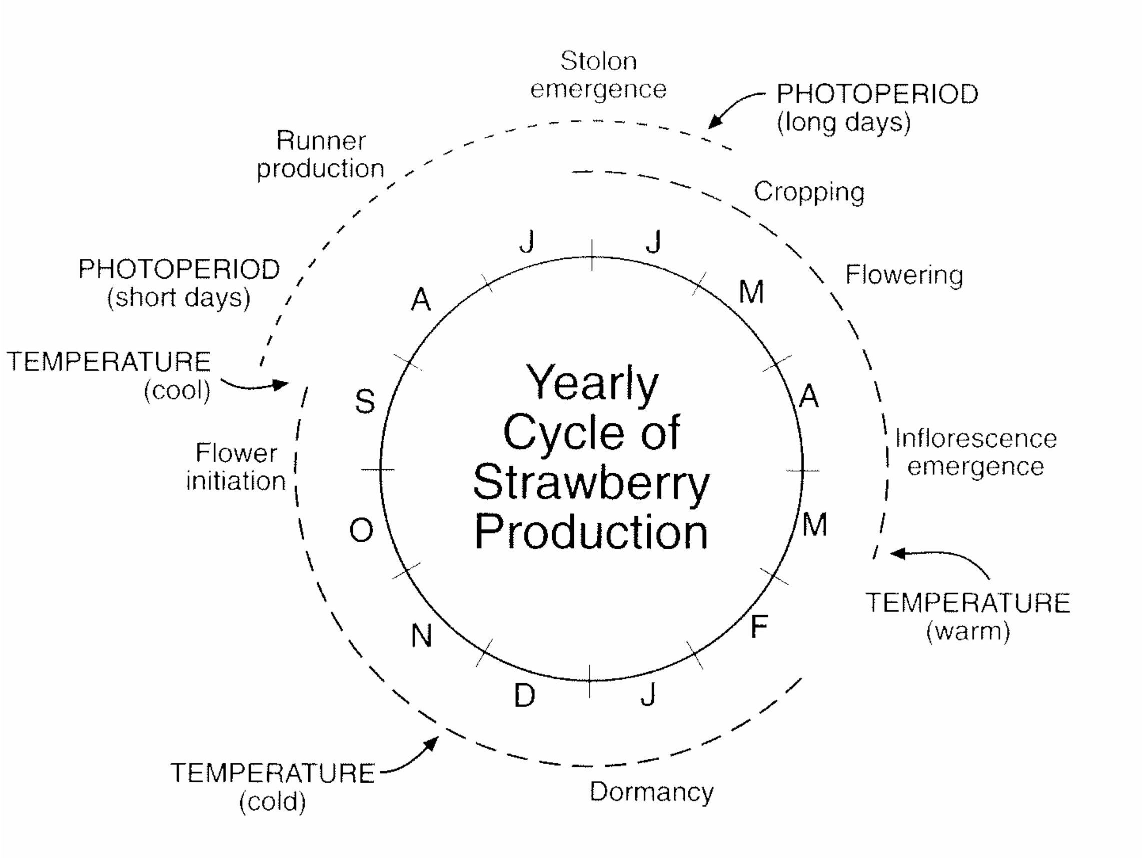
Strawberry production schedules depend heavily on the environment in which they are grown. Short-day strawberries form flower buds in the field during late summer and early autumn. The minimum number of short-days necessary to induce flower bud initiation is thought to range from 7-24 (Hancock 1999), although more recent research indicates that temperature also plays a much more important role than previously understood (Hollender et al. 2011). Generally, higher temperatures, around 30° C, mean that more than 20 short-days are needed for strawberries to form flower buds, while in temperatures closer to 24° C, the plants only need 10 short-days (Hancock 1999). After flowering and fruiting in early summer, short-day strawberries begin producing stolons in the long days of July and August, stopping only when the shorter days of autumn begin (Hancock 1999). Different cultivars have been bred to fruit later in the season, so it is possible to have short-day strawberries producing for most of the summer.

Day-neutral cultivars will produce flower buds, regardless of day length, between 1-2 months after planting. Like the short-day cultivars, day neutral flower production varies based on temperature, with ideal flower bud initiation temperatures between 18-26° C and total inhibition of flower bud initiation above 30° C (Hancock 1999). Stolons are produced throughout he season (Martin and Tepe 2014).

Leaves in both types of strawberries are produced throughout the season, but primarily during long days, and stop producing once the temperature drops below 0° C (Hancock 1999). Most root growth occurs during the cooler spring and autumn. Interestingly, root temperature seems to also have an effect on above ground growth, with temperatures above 30° C inhibiting overall plant growth, (Hancock 1999). Temperature's role in regulating flower bud initiation and development for both types of strawberries could have important implications for future indoor, containerized growth.

Both types of strawberries also enter a dormant period initiated by short days and lower temperatures, and require a chilling period of between 7 and 20 days depending on the cultivar (Bolda 2008). Newer cultivars designed for tropical and subtropical areas, such as Israel, have been developed to reduce the need for chilling requirements (Hancock 1999). The total number of weeks or days required for each step of a strawberry plants growth and development varies highly with different cultivars bred for different parts of the world, so creating a general crop production schedule is quite difficult. Figure 2 demonstrates a general monthly production schedule for Northern Hemisphere, temperate growers.

Figure 2: Model yearly strawberry crop production cycle (From Hancock 1999).



Many growers purchase new strawberry plants as bare-root plants when they are ready to begin production. In California, for example, high-elevation nurseries (1000-1300 meters) plant strawberries in early spring and dig up the plants in October. These "fresh-dug" plants can be sold to winter growers in California and Florida (Martin and Tepe 2014). Depending on where the nurseries are located and what cultivars are grown, winter growers might need to chill the fresh-dug plants for an additional period prior to planting (Bolda 2008). Low-elevation nurseries plant strawberries in the spring as well but harvest them after they've gone dormant in the fall and store them until the following spring (Galletta and Himelrick 1990). These "frigo" plants get their cold period either in the field or in cold storage, and are ready to sell to spring and summer growers as soon as it is warm enough (Rowley et al. 2010).

Recently, strawberry propagation using plugs has become more popular (Hokanson et al. 2004). Plugs are grown using the runner tips, or stolonate crowns from mother plants, grown either in the field or in a greenhouse. The runners are harvested and immediately rooted in cell trays or used in tissue culture before transplantation to cell trays. With proper care, plugs can be ready for transplant within four weeks (Rowley et al. 2010). Plugs can be mechanically planted more easily and require less water for root establishment, and do not suffer any root damage from being dug up unlike bare-root (Hokanson et al. 2004).

Once growers have their plants, there are two classic ways of growing strawberries outdoors in the United States: using a hill or using matted rows (Martin and Tepe 2014). In the hill system, the crowns are the primary source of production, with runners removed throughout the season. Hill systems often use a ‘plasticulture’ plastic mulch that covers a raised bed 15-25 cm high, with drip irrigation lines underneath. Day-neutral strawberries are usually grown in a hill system; the first set of flowers are usually removed to promote vegetative shoot and root growth, and the rest of the flowers come in flushes for 1-2 seasons before the plants are pulled up (Hancock 1999, Martin and Tepe 2014). Irrigation is usually necessary, with 1-1.5 meters of water recommended throughout the season (Carrol et al. 2015).

In a matted row system, strawberries are grown on flat beds with either drip tape or overhead irrigation. Short day, or June-bearing strawberries usually grow in matted row systems for 3-5 seasons. As with day-neutrals, the first flowers are removed, although the practice continues for a full season with short-day strawberries (Hancock 1999). Irrigation is recommended, especially during flowering in spring, with 60-70 cm suggested throughout the season. Stolons are usually allowed to grow to a certain extent, then moved into the middle of the row. At the end of the season, growers “renovate” their rows by removing the initially planted mother plants to favor the new daughter plants from the stolon.

In some parts of Asia, Europe, and, more recently, the United States, growers will use plastic tunnels or greenhouses to grow strawberries. Low tunnels can be built over strawberry rows to extend the season on either side of the warmer months, and can also provide rain protection (Hancock 1999) and reduced insect and disease pressures. Research at the University of

Minnesota has shown a high potential for low-tunnels to extend the season of day-neutral strawberries into late fall (Petran et al. 2015).

High tunnels are also used worldwide for strawberry production, especially in Europe (Hancock and Simpson 2004). High tunnels can be more expensive and more difficult to construct than low tunnels, but in the right climates can be used for year-round production. Like low tunnels, high tunnels can raise the temperature inside the tunnel and protect the strawberries from winter winds and freezes (Rowley et al. 2010). These benefits mimic conditions inside a greenhouse, but avoid the costs of constructing and operating a greenhouse.

Some growers around the world do use greenhouses for strawberry production. In Japan, growers plant strawberries in a coir/peat media mix on elevated cultivation benches inside a greenhouse. Irrigation, fertilization, and temperature can all be controlled via computer. Plant starts can come from outdoor nurseries or indoor runner production, where runners can be potted into pots placed just below the elevated benches (Takei 2010). The Japanese have used some form of protected production for strawberries since 1910, when strawberries were planted in concrete blocks placed on a hillside and covered with plastic (Oda and Kawata 1993). The more modern greenhouse production system allows for year-round production (Takei 2010).

European strawberry producers also utilize greenhouses. The Dutch are the primary greenhouse growers, with over 350 hectares of strawberries planted under glass producing 29 million kg in 2014 (Statistics Netherlands 2015). European growers also tend to use a coir/peat mixture, and stagger their plantings to get year-round production. Dutch and Belgian growers use cultivars with dormancies that can be broken using night interruption lighting, bypassing the need to chill their plants and facilitating year-round production (Lieten 2012).

Strawberries can be harvested when they are three-quarters colored which will store well, or when fully ripe if they are to be sold sooner. Strawberries intended for processing are usually picked later (Hancock 1999). After harvest, the fruit can be cooled and have a post-harvest life of 5-9 days depending on how they ripe they were at harvest and how they are stored (Bolda 2008).

B. Current Production Statistics.

As of 2014, the United States was the world's largest strawberry producer. The primary strawberry producing states are California, with 88% of national production, followed distantly by Florida, with 8% of production (Brennan et al. 2014). Oregon, North Carolina, and Washington also produce strawberries, but at nowhere near the levels of California. In 2012, there were almost 24,000 hectares of land in strawberry production (Figure 4), 15,500 hectares of which were in California. The United States produced 1.4 billion kilograms of strawberries (Figure 5), with 1.2 billion kilograms coming from California alone. According to the USDA (Figure 5) the value of the United States' strawberry production was over $2 billion (USD) in 2012 (ERS 2012).

Strawberry consumption in the United States was at 3.3 kilograms per capita in 2011 (ERS 2012). Not all the berries consumed in the United States are grown here, however—110.5 million kilograms were imported in 2011 (Figure 3), making the United States the 4th largest importer in the world. Most of those imports come from Mexico, primarily in winter months (ERS 2012). The United States is the second largest exporter of strawberries, after Spain, with exports valued $359.8 million (USD) in 2010 (Wu et al. 2012). The primary recipient of American strawberries is Canada, receiving 118 million kilograms of strawberries in 2012 (ERS 2012).

Figure 3: Strawberry imports and exports in the United States (Adapted from ERS 2012).

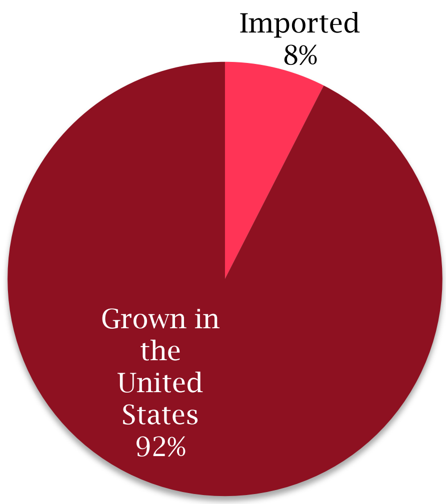


Figure 4: Hectares of land in strawberry production in the United States (Adapted from ERS 2012).

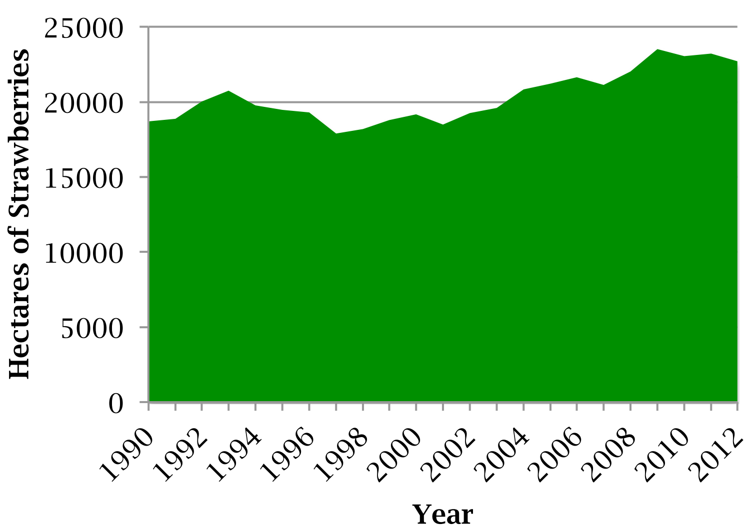
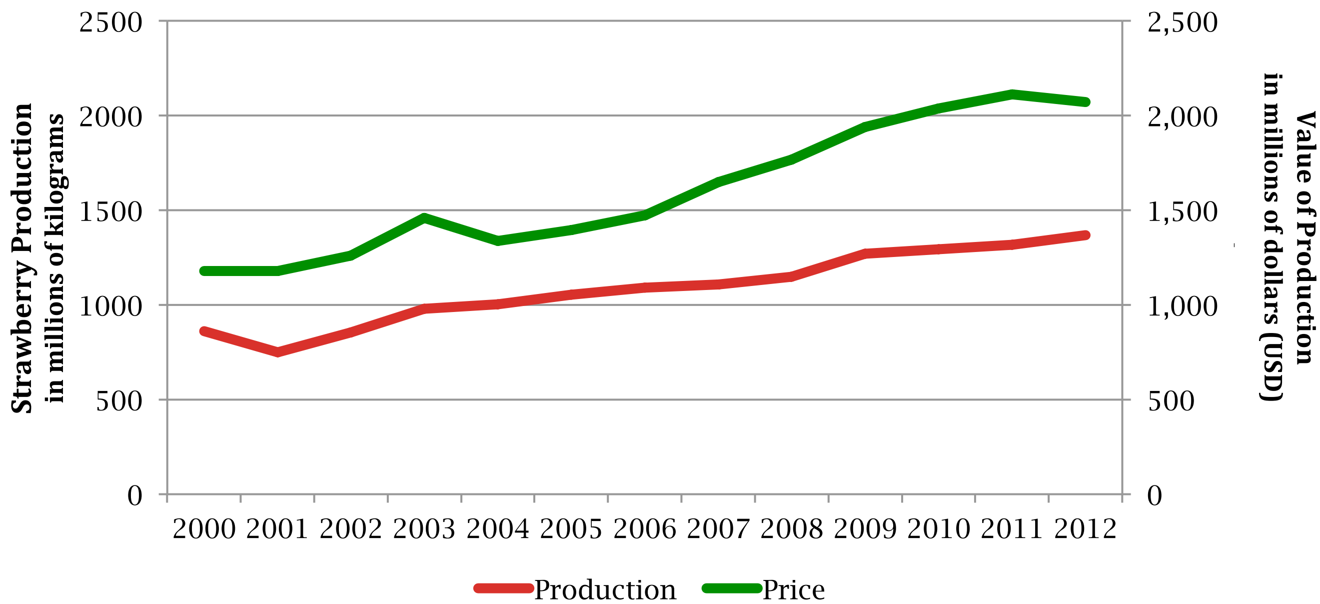


Figure 5: Value (in millions of dollars; USD) and production (millions of kg) of strawberry industry in the United States, 2000-2012 (Adapted from ERS 2012).



Spain, Turkey, Egypt, Mexico, Poland, and South Korea are other leading worldwide producers of strawberries (Wu et al. 2012). Figure 6 shows worldwide trends in strawberry production between 2000 and 2011, with total production in 2011 shown in Table 2. It should be noted that data on Chinese strawberry production are harder to obtain, but some estimates show Chinese production around 2.1 billion kilograms in 2012, surpassing production in the United States by almost 1 billion kilograms (Scott and Lei 2012). Spain exports more strawberries than any other nation, mostly to Europe, making about €400 million per year from exports (Goni 2011).

Figure 6: Strawberry production in the major strawberry producing countries (Adapted from ERS 2012)

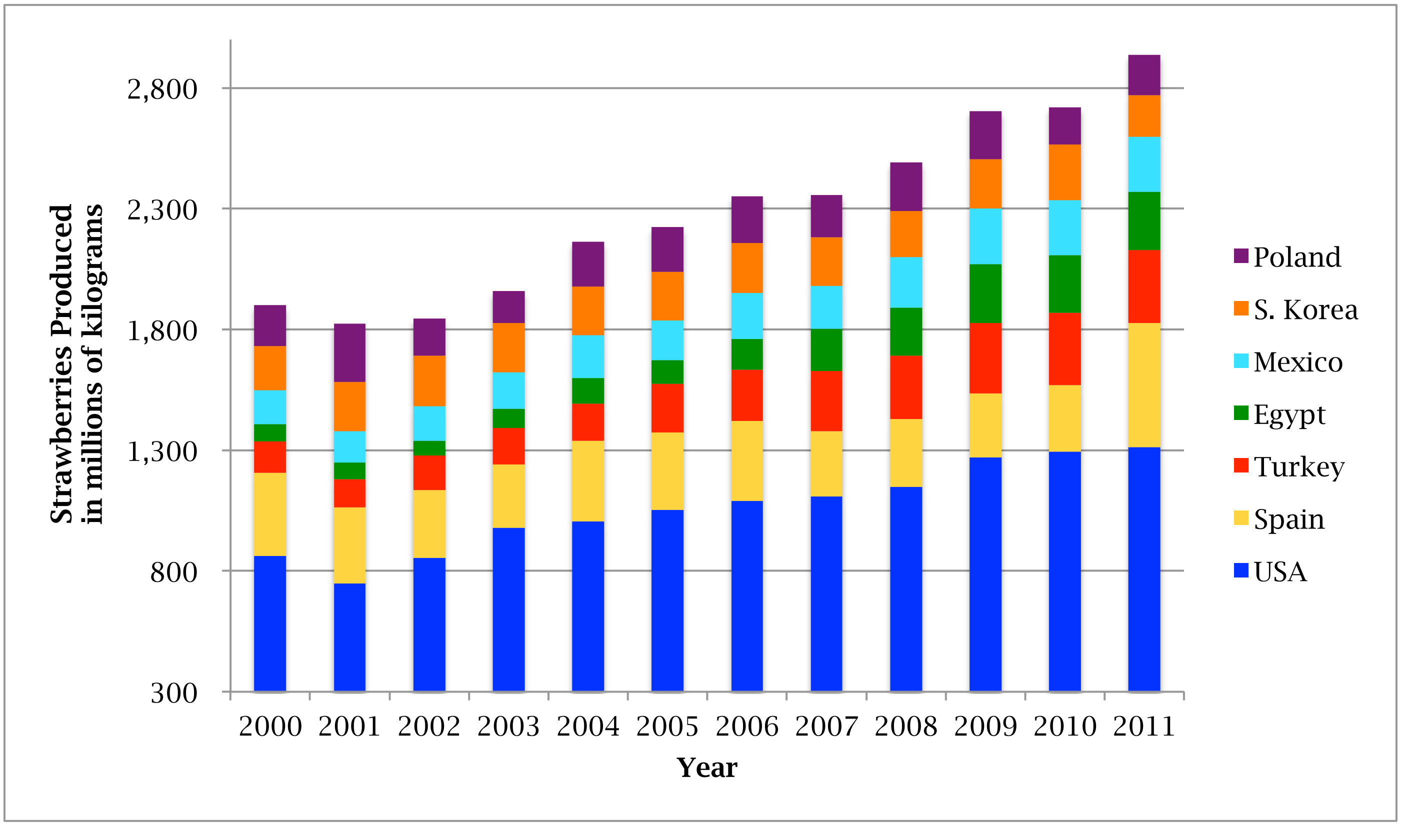


Table 3: Worldwide strawberry production in 2011 (Adapted from ERS 2012 and Scott and Lei 2012).

Country	Kg. of Strawberries Produced
USA	1,312,960,000
Spain	514,027,000
Turkey	302,416,000
Egypt	240,284,000
Mexico	228,900,000
S. Korea	171,519,000
Poland	166,159,000
China*	2,100,000,000

As most of the production of strawberries in the United States occurs in California, many of the popular cultivars in the United States can be found in California, coming either from the University of California or from Driscoll's own breeding programs. 'Albion,' a cultivar released by the University of California is one of the most popular known for its good fruit size and yield, two of the most important traits for breeders and growers (Lopez-Aranda et al. 2011). The Driscoll's cultivars are not well described as there are less data on these privately created cultivars, but are known to be adapted to California growth. In the Pacific Northwest, the 'Hood' cultivar from OSU and the USDA in Corvallis is the best adapted for processing (Hummer and Hancock 2009).

American cultivars, such as Florida's 'Sweet Charlie,' are grown outside of the United States as well (Table 4), due to their more adaptable traits, though there are certainly other cultivars from foreign breeding programs. South Korea's 'Maehyang' cultivar, from the Nonsan

Strawberry Experiment Station of the Chungcheongnam-do Agricultural Research and Extension Service, was bred specifically for weak dormancy, an important trait for indoor strawberry forcing in South Korea (Kim et al. 2004), while Turkey's 'Osmanlı' cultivar was bred to thrive in the Turkish climate (Kurgi et al. 2012). European growers use several American cultivars, but the Dutch 'Elsanta' still remains extremely popular, especially in Northern growing areas to which 'Elsanta' is well suited (Krüger et al. 2012).

Table 4: Popular worldwide strawberry (*F.* x*ananassa*) cultivars (Adapted from Hummer and Hancock 2009; Kim et al. 2009; López-Aranda et al. 2011; Kargı et al. 2012; Krüger et al. 2012).

Cultivar	Provenance	Geographic Area
Albion	University of California-Davis	California, USA, Mexico
Camarosa	University of California-Davis	California, China, Spain
Chandler	University of California-Davis	California, China, Spain
Amesti	Driscoll's	California
El Dorado	Driscoll's	California
Jubilee	Driscoll's	California
Florida Festival	University of Florida	SE USA, Mexico, Spain, Turkey
Sweet Charlie	University of Florida	SE USA, Turkey
Hood	USDA/Oregon State University	NW USA
Maehyang	Chungcheongnam-do Agricultural Research and Extension Service, South Korea	South Korea
Osmanlı	University of Çukurova, Turkey	Turkey
Elsanta	Wageningen University and Research Centre, The Netherlands	Europe

IV. PROPOSED CROP TRANSFORMATION

A. Crop Production Change(s) for the Future.

To successfully grow *F.* x*ananassa* year-round in Minnesota and other Northern climates, many different aspects of worldwide production need to be combined and implemented together. One of the biggest hurdles for indoor production is the high-water requirement of strawberries. Hydroponic or aquaponic systems could be used to solve this problem. Researchers from the University of Arizona and the University of Arkansas have begun working on fertigation recipes for hydroponic strawberries, based on Japanese practices (Kubota and Kroggel, 2013). Other indoor growing methods have used drip irrigation systems, but often require multiple watering and fertilizing per day (Lantz et al. 2010). Hydroponics could provide a way to significantly reduce water needs in an era where water is becoming more expensive and unavailable.

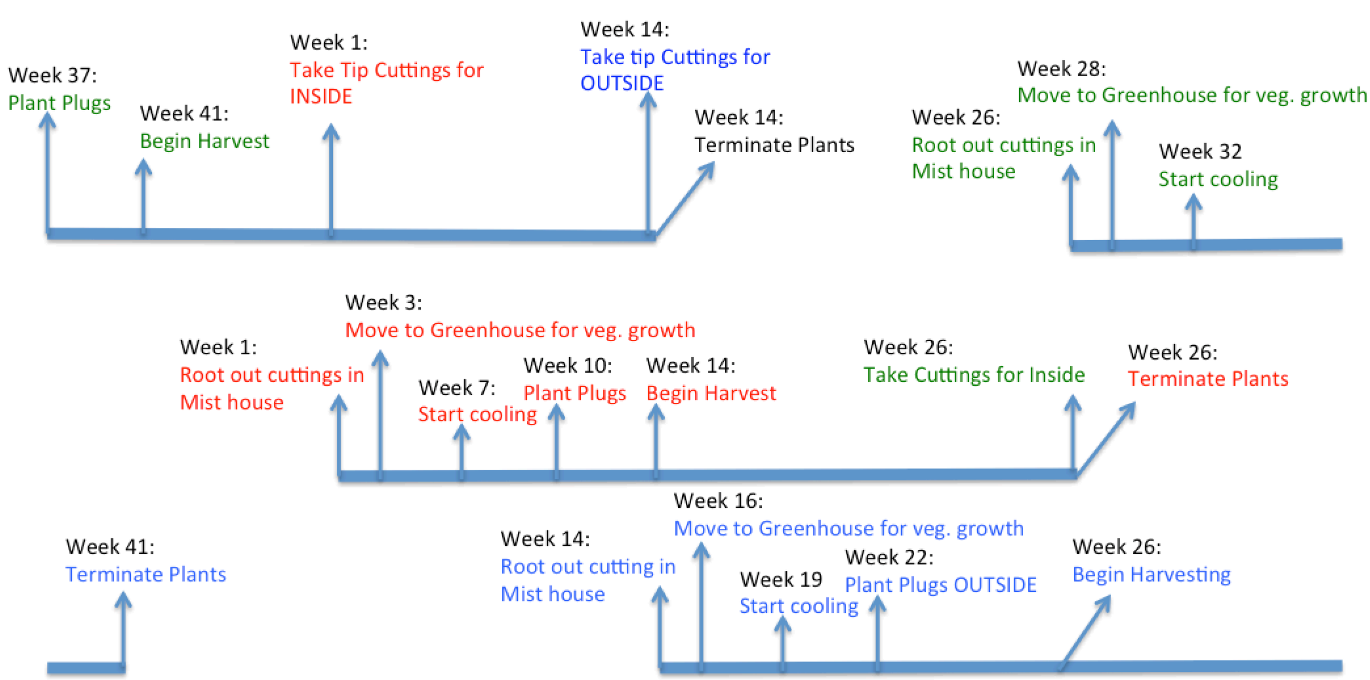
For Minnesota and Northern indoor growers to be successful, new cultivars should be developed that select for lower light needs, and shorter, warmer cooling requirements. Most strawberry cultivars in the United States, as mentioned, come from California and are designed for growth in the California Mediterranean climate. New cultivars, more similar to those used in Europe perhaps, could be developed to thrive in the low light conditions of Northern winters, reducing the need for intensive greenhouse lighting. Furthermore, to facilitate year-round growth, cultivars should have a lower minimum temperature for flower bud initiation and development.

This new winter strawberry growing process would involve planting day-neutral strawberries in mid-summer inside the greenhouse in a hydroponic or aquaponic system. The plants would be ready to harvest around the time that outdoor day-neutral berries stop producing (late fall) and could produce all winter and spring. Towards the end of the winter, runner tips could be removed and propagated into cell trays. Once rooted, these trays could be placed into cold storage for the summer to get their cooling requirement. The process would begin again in mid summer, with the cooled propagules planted into the hydroponic system.

B. A New Production Schedule for Indoor Strawberries.

A new strawberry production schedule that would allow growers in Minnesota to produce strawberries year-round (Figure 6). Strawberry plugs should be planted in gutters around week 37 and should be ready to harvest by week 41. After several months, tip cuttings will be collected on week 1 and week 14. These cuttings will be rooted in a mist house for two weeks, after which the new crowns should be grown for about four weeks. The new plants should then be put into cold storage for three weeks before being planted. The cuttings from week 1 will be planted in gutters in the greenhouse, while the cuttings from week 14 will be used for outdoor field production. On week 26 another set of cuttings will be taken from the indoor plants for planting by week 37 to begin the process anew. A new set of stock plants should be introduced after several cycles to ensure that no diseases or viruses have made their way into the growing system.

Figure 6: New crop production schedule for greenhouse production of strawberries.



For a hydroponic system, the strawberry plugs should be planted into a sterile media mix of 50% perlite, 25% coconut coir and 25% peat moss, with two liters of substrate per plant (Kubota and Kroggel 2013). The strawberries will be planted in hanging or tabled gutters, with a fertigation system constructed so that one emitter is located next to each plant. The gutters will drain into a catchment system to be recycled through the hydroponic system. The fine calibration of nutrient levels provided in the hydroponic system, both through nutrient content of the water and the frequency of watering, will allow for appropriate plant nutrient levels and maximum yield. Current recommendations, based on a Japanese strawberry system, can be seen in Table 5. Application should be in frequent, small amounts (33 mls per plant) to prevent overwatering, drying, or poor drainage (Kubota and Kroggel 2013).

Table 5: Major elements in Hydroponic fertilizers, in mg/L or ppm. Jensen-tomato recipe is shown as a comparison (Adapted from Kubota and Kroggel 2013).

Hydroponic Recipe	N (NO_3^-)	N (NH_4^+)	P (PO_4^{3-})	K	Ca	Mg	S (SO_4^{2-})
Yamazaki-strawberry (full strength)	70	7	15	117	40	12	16
Jensen-tomato (HALF strength)	95	0	24	175	100	30	58

Though perhaps more complicated and expensive, an aquaponic system could also grow strawberries using this new method. A similar system could be constructed, but rather than feeding fertilizer through the fertigation system, the waste from fish tanks would provide nutrients (Roosta and Afsharipoor 2012). Depending on the fertility of the fish waste, the substrate in which the strawberries are planted may need to be adjusted. While hydroponic strawberry production occurs in several places around the world, aquaponic strawberry production is quite rare, and resources for growers are limited.

In either an aquaponic or a hydroponic system, greenhouse conditions should be programed to maximize strawberry growth and yield. As the cultivars used would be day-neutral, intensive lighting would not be necessary. Supplemental lighting in the greenhouse could be programed to provide light on particularly dark days to ensure vigorous photosynthesis, but as day-neutral strawberries have been shown to be truly insensitive to photoperiod (Stewart and Folta 2010), growers would not need to spend extra time or money lighting their greenhouses. As mentioned, Day-neutral plants do, however, require certain temperature conditions to initiate and develop flowers, so growers would need to program their greenhouses to maintain specific temperature ranges. Further discussion of temperature conditions can be found in the next section.

Taking cuttings from plants already growing in the greenhouse and fulfilling their cooling requirements in cooled greenhouses or coolers, rather than in the field, will also expedite growth and save money. Growers will not have to wait for producers to ship them bare-root plants that could be delayed due to weather or their dig date, nor will they have to worry about buying plug trays or wondering if they've truly had their cooling requirement fulfilled. Taking their own cuttings will also cut out the 'middle-man' that some growers use to purchase runner tips for rooting; growers can use their own runner tips.

Shipping and marketing of these new winter strawberries will use the same techniques and strategies as "seasonal" strawberries, but growers will likely be able to achieve higher sales due to the rarity of local strawberry fruits in the middle of winter. Some studies have found consumers willing to pay as much as double the regular-season price for locally produced fruit in the 'off-season' (Rowley 2010). At the University of Minnesota farmer's market, locally produced, organic strawberries sell for as much as $7 (USD)/pint in July—growers could potentially sell their strawberries for as much as $14 (USD)/pint in January.

C. The New Strawberry Ideotype.

To achieve this new crop schedule and sell strawberries year-round in Minnesota, several traits should be incorporated into a new strawberry ideotype ideal for indoor, efficient strawberry production. Many day-neutral strawberry cultivars require a dormancy period of between 675 and 1000 hours in a conditions of -1 - 10° C (Stewart and Folta 2010). To grow successfully in the new, year-round, Minnesota production schedule, new cultivars should be bred to have a shorter dormancy requirement, closer to two weeks, or ~350 hours. While studies indicate that the ideal temperature for dormancy is right around 0° C, the new cultivars should be have an ideal dormancy temperature closer to 3° C. These changes would allow growers to more quickly turn out new plants with vigorous growth and to save money on freezers required for cooling. Temperatures closer to 3° C could allow growers to cool starts in a refrigerator rather than a freezer, which cost significantly less.

Another important trait of this new cultivar is the ability to produce crowns and flower buds at a lower temperature. Studies show day/night temperatures of 18/14° C as the ideal for fruit production (Hancock 1999); if the new cultivar could reach FBI and FBD at closer to 15/14, growers could save a lot of money heating their greenhouses during the winter. Similarly, day/night temperatures of 30/26° C inhibit all flower bud initiation in day-neutral strawberries (Hancock 1999). While a greenhouse is unlikely to reach 30° C during the winter, ensuring greenhouse temperatures lowers that 30°C during the summer could be difficult. Therefore, developing a cultivar that can withstand heat during the day better could help prevent losses for growers in hotter times of year. These traits would also help strawberries (propagated from those in the greenhouse) growing outside produce fruits earlier in the spring and later in the fall. Adjusting the minimum and maximum temperatures conditions under which this new cultivar can produce flowers and fruits will help make year-round strawberry production in Minnesota viable.

Strawberry flavor and appearance does not need to be significantly changed in order to achieve indoor strawberry production in the Midwest. However, a new strawberry cultivar, known as the 'Pineberry' has recently shown some popularity in Europe. The Pineberry keeps the white color of *Fragaria chilonensis*, the wild Chilean strawberry, and is slightly smaller with a different, though sweet, flavor profile (Osbourne 2014). While interest in the Pineberry has so far been low in the United States, it could be a cultivar to explore in order to increase interest in the local Midwest strawberry industry. While developing a new, ideal, indoor strawberry cultivar, researchers should consider the Pineberry as well.

Finally, the cultivar best suited for indoor production should have relatively standard fruit size. While most cultivars have a range of fruit sizes, developing a standard size trait could make indoor mechanization feasible and possible. Several studies have already looked at using robotic harvesting in raised-trough, indoor conditions, and primarily use size and color to determine fruit ripeness (Qingchun et al. 2012). If the cultivar used in Midwest greenhouses could have a distinct size at ripeness, the use of robotic harvesters would likely be more efficient and, after several seasons, financially worthwhile.

With these changes, a new strawberry cultivar could thrive in an indoor strawberry production system in Minnesota that would allow for the production of strawberries year-round. The combination of the new strawberry ideotype and modified greenhouse conditions will help growers save money while also making money by selling locally grown strawberries in the off-season. As the demand for local food increases, year-round strawberry production is a niche waiting to be filled.

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